DEVELOPMENTS IN ULTRA-STABLE QUARTZ OSCILLATORS FOR DEEP SPACE RELIABILITY

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Abstract

For over four decades, the Applied Physics Laboratory of Johns Hopkins University (JHU/APL) has supplied the U.S. military and commercial space sectors with a quartz oscillator of unsurpassed performance and reliability. Referred to as having Ultra-Stable performance, this oscillator has been given the nomenclature of USO. The current USO, at 1.2 kilograms and 1.1 watts steady-state power consumption, features time- dependent drift (aging) of less than 1×10^{-11} per day and fractional frequency variance approaching 1×10^{-13} over the range of 1 to 100 seconds.

Our paper will present performance data and describe the unique advantages afforded by the use of quartz oscillators in deep space, including in-flight data that demonstrates no degradation to long-term frequency by repeated radiation exposures. We will also present an outlook of technology projects planned for the next 5 years, including the use of Kalman filtering, direct digital synthesis, and alternative piezoelectric materials. We will present our viewpoint that further development in quartz resonators for space applications will only gain in importance as communication needs expand into interplanetary networks.

I. INTRODUCTION

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has supplied the U.S. military and commercial space sectors with ultra-stable quartz oscillators (USOs) that have figured prominently in many missions of high merit. Starting with the TRANSIT satellite navigation program and continuing with the New Horizons interplanetary mission to the Pluto-Charon system, JHU/APL has continuously found innovations in supporting weight, power, and size reduction while steadily increasing stability performance. Figure 1 shows the evolution of our USO performance over four decades of service. The USO currently in fabrication features daily time-dependent drift (aging) of less than 1×10^{-11} per day and fractional frequency variance approaching 1×10^{-13} over time intervals of 1 to 100 seconds.

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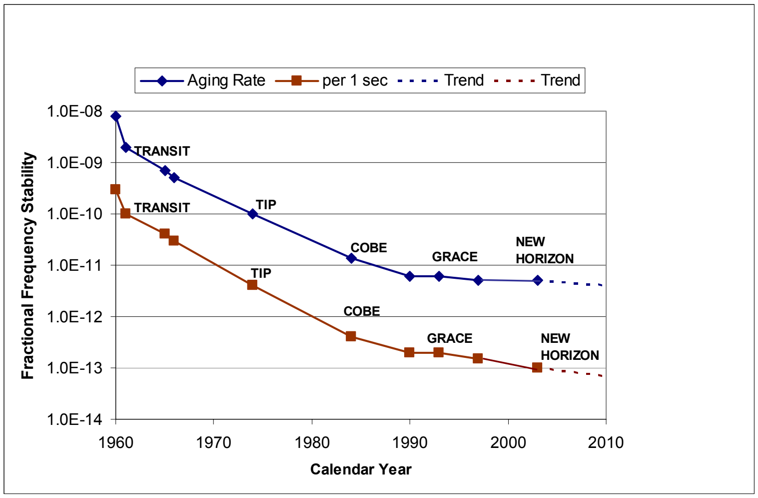

Figure 1. Incremental improvement in USO performance since 1960.

Summary of Recent History for JHU/APL USO Mission Deployment

Quartz-based oscillators have demonstrated an excellent history of reliability in space, often outliving the rest of the satellite or even the usefulness of a mission. A good example of the latter was demonstrated in the Transit satellite navigation system. Transit relied on JHU/APL built USOs for its space-based frequency reference, and had several USOs operating continuously for periods of 15 to 21 years **[1]**. Transit continued to operate reliably, but was eventually rendered obsolete by the Global Positioning System (GPS). At present, the following chronology of missions containing JHU/APL USOs remain in active service.

Ocean Topography Experiment (TOPEX) launched in 1992 into Earth orbit to monitor ocean climate. While originally built for a minimum 3-year mission life, TOPEX continues to give insight into El Niños and other significant weather patterns. Measurements from the satellite's altimeter and radiometer allow scientists to chart the height of the seas across ocean basins with an accuracy of less than 10 centimeters **[2]**. The JHU/APL USO provides frequency references for the altimeter and supports other critical functions such as timekeeping on the spacecraft.

Mars Global Surveyor (MGS) was launched into deep space in 1996 and began collecting orbital science data at Mars in 1998. While the primary mission ended in 2000, the spacecraft continues to supply data to mission scientists and has completed over 25,000 science orbits **[3]**. The JHU/APL USO supports precise downlink radio science measurements to enable scientists to determine the precise shape of the planet and structure of the atmosphere by passing high-stability radio waves through the planet's atmosphere and on to Earth.

Mid-Course Space Experiment (MSX) launched into Earth orbit in 1996 and, during its primary "cryogen phase," successfully demonstrated the ability to track missiles **[4]**. MSX is now focused on celestial and terrestrial backgrounds, surveillance demonstrations, contamination, and environmental research. While this JHU/APL spacecraft was conceived and built to support the Strategic Defense Initiative, the array of instruments on MSX has allowed the mission to evolve and continue providing useful scientific data. The JHU/APL-built USOs on board MSX provide frequency reference signals for the high-speed data downlink and other spacecraft subsystems.

Cassini-Huygens was launched into deep space in 1997 and arrived at Saturn in June 2004. It is now providing exciting images and science data about Saturn's moons, rings, and atmosphere **[5]**. The JHU/APL USO provides a frequency reference to the communications transponder, forming an integral part of the radio science subsystem. The radio science measurements provide detailed information about the structure of Saturn's rings and atmosphere.

Gravity Recovery and Climate Experiment (GRACE) was launched two spacecraft into Earth orbit in 2002. The twin satellites utilize a dual frequency inter-satellite ranging instrument to measure the relative position of the satellites. From this information, the relative velocity between two satellites in the same orbit is known and then gravitational pull is computed, significantly improving our knowledge of Earth's gravity fields **[6]**. The accuracy of the ranging measurement is highly dependant on the reference oscillator performance, and is accurate to about 40 micrometers in 220 km with JHU/APL-built USOs.

RELEVANCE OF QUARTZ TECHNOLOGY IN DEEP SPACE

Without exception, the ability to accurately keep and transmit time directly influences the performance of space systems for navigation, guidance, and secure communications. The USO of JHU/APL has demonstrated itself in over 300 critical space applications as an asset to the strategic timekeeping and signal technologies of the United States. Therefore, any enhancement to the JHU/APL USO that extends its mission performance without diminishing reliability is valuable to the operations of deep space communication and navigation systems. Specifically, the JHU/APL USO has been used in space without suffering catastrophic failure, unlike certain atomic standards. As a frequency source, the USO outperforms atomic standards with respect to phase noise and short-term stability, falling short only with respect to long-term drift.

This is because a major drift mechanism (aging) for a quartz resonator is related to time-dependent chemical activation of the vapor-deposited metal electrodes used to stimulate the quartz crystal into vibration. As time accumulates, these electrodes tend toward passivity, given a constant thermal operating environment. This drift has been established to follow a functional dependence with time of the form $A \cdot \log(B{\cdot}t + 1)$ and, in the case of the quartz resonators used in the USO, diminishes to a daily rate of less than 1×10^{-11} over long time periods. This highly predictable, long-term characteristic is associated with operation of the quartz resonator in the vacuum of space, rather than in the atmospheric gases of Earth where any leakage of the quartz resonator's housing will induce deterioration over time.

The in-flight frequency drift of quartz oscillators in the space environment is very good, often much better than that measured before launch. For example, the quartz oscillator in the first Milstar satellite, FLT-1, recorded a total frequency drift of less the 5×10^{-10} for a 430-day period, beginning in 1994. This was reported to be nearly a tenfold improvement over its pre-launch drift rate.[1] Our experience at JHU/APL has been similar. NOVA 3, one of the last Transit satellites, was measured during ground testing to have a daily drift rate of -4.7×10^{-11}, but in flight had a daily drift rate of only -9×10^{-13} **[1]**. This improvement in drift rate under space operation was common for the many Transit USOs, and continues to be observed in more recently built JHU/APL USOs. Figure 2 shows the in-flight frequency drift with time for 13 ultra-stable quartz oscillators used in low Earth-orbiting satellites delivered by JHU/APL since the early 1990's. Many of these oscillators show the logarithmic reduction of frequency drift expected for their long-term aging behavior.

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[1] M. Bloch, *et al.* , 1996, *"Performance data on the Milstar rubidium and quartz frequency standards: comparison of ground tests in a simulated space environment to results obtained in orbit,"* in Proceedings of the IEEE International. Frequency Control Symposium, 5-7 June 1996, Honolulu, Hawaii, USA (IEEE 96CH35935), p. 1060.

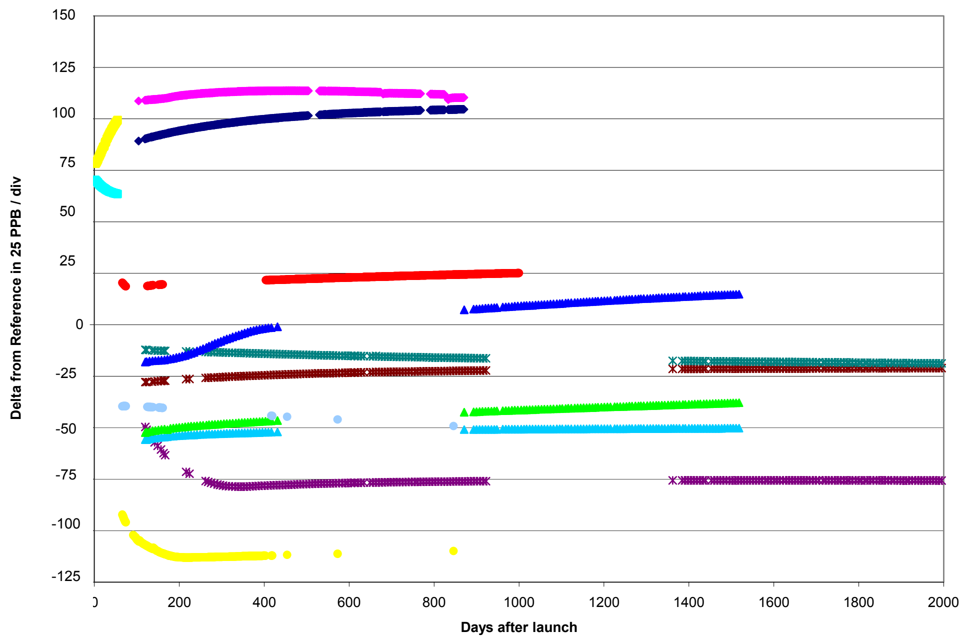

Figure 2. Frequency drift of 13 ultra-stable oscillators in low Earth orbit.

JHU/APL believes the development of a USO that could surpass the long-term drift rates of rubidium-gas-cell-based atomic clocks would enable greater operational utility for future deep space communication links and hub systems where end-of-life (EOL) mission scenarios extend significantly beyond a decade. Such an EOL requirement in remote operation extends well past the expected life of current atomic clock technologies. In base-stations for commercial wireless CDMA telecommunication, disciplined quartz oscillators are preferred for their operational reliability and cost-effectiveness to rubidium atomic clocks. The value of applying disciplining technology to JHU/APL USOs for space applications is certainly analogous in this regard and perhaps even more pertinent. Also, because of the current stress in the industrial frequency control environment, it appears appropriate that JHU/APL undertake the initiative to extend the benefits of a disciplined USO to the critical technologies of the United States Government.

II. DEMONSTRATED PERFORMANCE IN A VARIETY OF FLIGHT MISSIONS

PERFORMANCE OF USOs IN DEEP SPACE

Deep space missions, in particular, require a reliable spacecraft and subsystems to yield success. These missions can take many years for the spacecraft to reach its destination and only then begin the useful part of collecting science data. The Mars Global Surveyor (MGS) and Cassini are two such examples where quartz-based USOs built by JHU/APL provide the critical frequency reference. The long-term frequency curves of these two USOs, shown in Figures 3 and 4, demonstrate well-behaved performance over the course of many years of continuous operation. In both Figures 3 and 4, the long-term drift of the onboard USOs show the expected logarithmically, diminishing aging characteristic of quartz resonators in space application. In the case of the USO in the MGS, the daily rate has decreased to less than 2×10^{-12} over the last 1200 days of monitored operation. For the Cassini USO of Figure 4, the daily rate has decreased to less than 5×10^{-12} over the last 1000-day period of monitored frequency, ending in mid-2002.

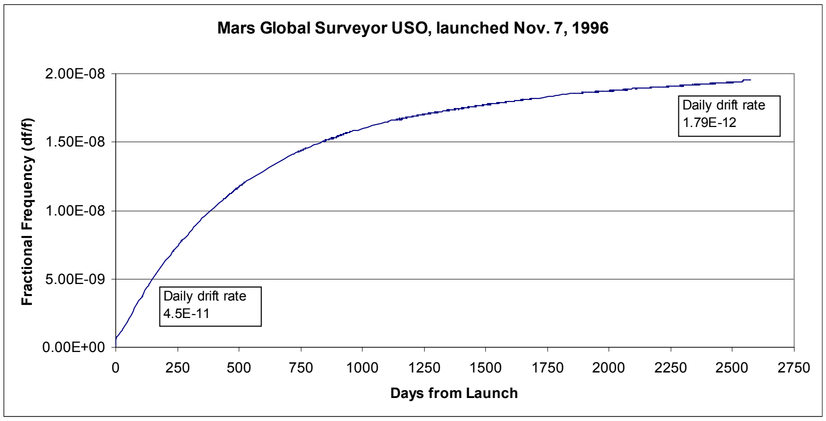

Figure 3. MGS USO frequency as measured from microwave carrier.

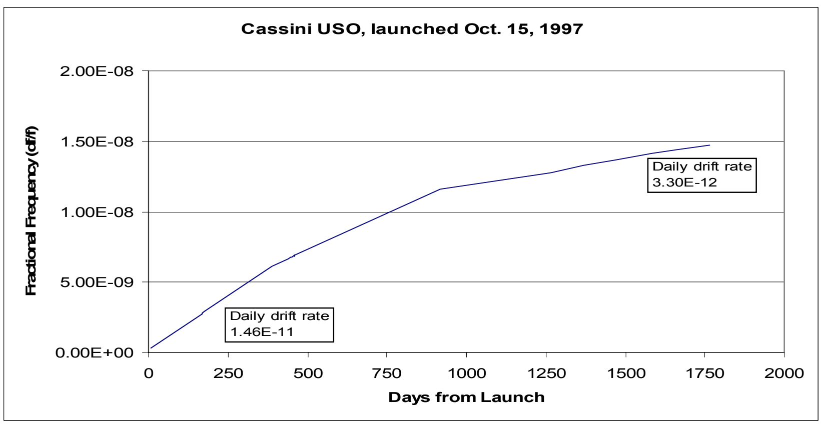

Figure 4. Cassini USO frequency as measured from microwave carrier.

PERFORMANCE OF USOS IN LOW EARTH ORBIT

Low Earth orbit missions are often shorter in duration than deep space missions, but can experience a more severe operating environment in the form of repeated exposure to low dose radiation. The long-term frequency performance of the USOs shown in Figure 2 as well as the frequency performance of the USOs in TOPEX and GRACE oscillators, shown in Figures 5 and 6, demonstrate no deviation in performance consistent with that expected from the radiation sensitivity of quartz resonators. Since it is expected that each of these oscillators should accumulate nearly 1000 rad (Si) per year of ionizing radiation and quartz resonators have measured frequency sensitivities to ionizing radiation of about 1×10^{-10} per rad (Si), it is apparent that the frequency change associated with this radiation cannot be cumulative in space operation. For the TOPEX USO, the total frequency drift observed over 912 days, ending in December 1997, was 12×10^{-9}, or a daily aging rate of about 1.3×10^{-11}. The total frequency drifts observed in GRACE A and GRACE B were 32×10^{-9} and 6.2×10^{-9}, respectively, over a 550-day monitoring period beginning within a week of the launch date. The so-called recovery of quartz resonators from the effects of low-dose irradiation has been observed in numerous laboratory experiments **[7,8]**.

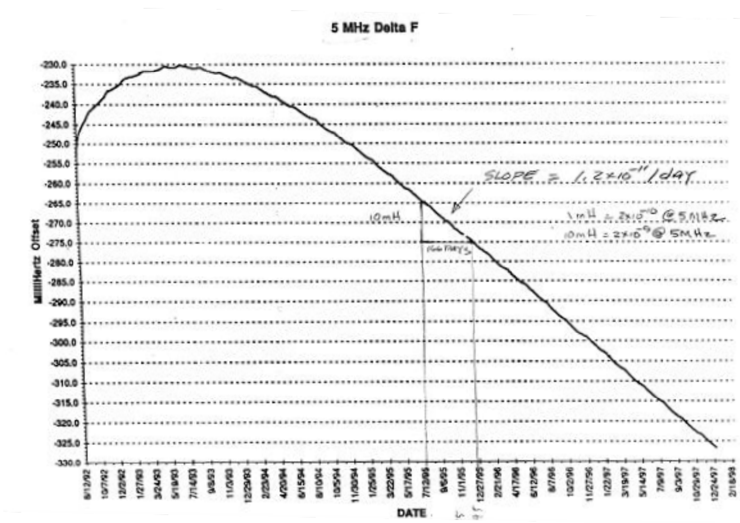

Figure 5. TOPEX USO frequency.

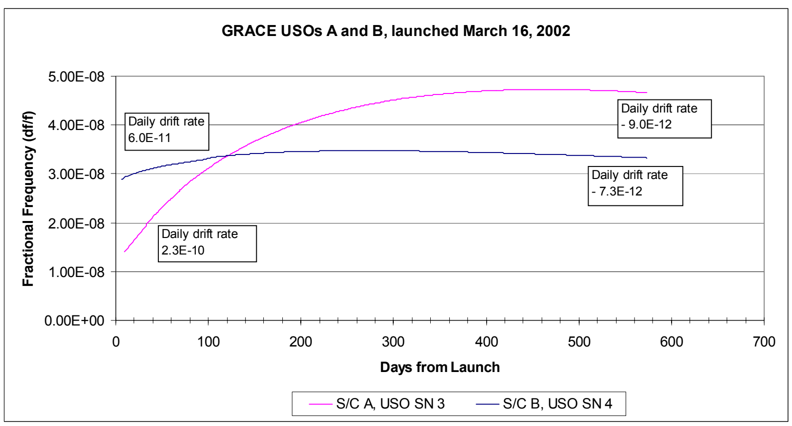

Figure 6. GRACE USO frequency as measured from microwave carrier.

A good example of the ability of quartz resonators to recover from radiation exposure while in the space environment is the Milstar FLT-1 data recorded during a peak in solar activity. Specifically, the frequency sensitivity of this oscillator from two solar flares of July and November, 2000, was detailed for analysis. In **[9]**, Camparo *et al.* found that Allan deviation was not deteriorated by solar flares observed over these 4 years. The radiation sensitivity of the quartz oscillator was found to follow a nonlinear relationship with particle flux, and the maximum frequency shifts of the quartz oscillator were in proportion to those typical of orbit simulation experiments in the order of 1×10^{-10} per rad (Si). All frequency shifts were transient, with the effects diminishing over 10 days. The onset of these radiation-induced frequency perturbations were well within the ability for ground control action and did not unduly disrupt satcom operations.

PERFORMANCE OF USO UNDER DEVELOPMENT FOR MARS TECHNICAL PROGRAM

JHU/APL is currently conducting work under the NASA Mars Technology Program (MTP) task # 1243213 to enhance the present USO technology through a design effort to significantly reduce mass and

power consumption while maintaining excellent fractional frequency characteristics. It is also desired that this USO will have the ability to perform in an ambient air environment with minor degradation to that measured in vacuum. The resulting USO from the NASA MTP effort will drive a direct digital synthesizer, also under development at JHU/APL, to add the capability of in-flight frequency agility. The DDS development aspect is discussed in the following section of this paper. The design improvements to our USO realized to date have further evolved the JHU/APL USO performance. The key specifications required from the USO for the NASA MTP development are:

Allan deviation	$< 5 \times 10^{-13}$ for time intervals from 1 to 100 seconds
Frequency change with temperature	$< 1 \times 10^{-12}$ / ^{o}C over 0 to +40^{o}C
Aging rate	$< 1 \times 10^{-11}$ per 24 hours after 30 days
Phase noise	< -95 dBc at 1 Hz offset referred to a 76.5 MHz carrier
Radiation sensitivity	$< 1 \times 10^{-10}$ per rad (Si) proton radiation
Typical mass	< 0.5 kg
Typical power after warm-up	< 0.7 W from +28 volts DC at +20^{o}C baseplate.

The specifications referenced above represent over a 60% improvement in mass and nearly a 40% improvement in power consumption over traditional JHU/APL USO specifications. The remaining specifications are those typically achieved with JHU/APL USOs using screened quartz resonators. The data of Table I summarize the frequency versus temperature performance of the MTP USO obtained so far in our development. In Table I, the total frequency change for the USO was measured to be about 1.2 $\times 10^{-11}$ or 3.0×10^{-13} per ^{o}C. This is well within our design goal of 4×10^{-11} or 1.0×10^{-12} per ^{o}C.

Table I. Frequency change with external operating temperature.

Plate Temp. (^{o}C)	Freq. change (ppb)	Supply (V)	Power (W)
+ 0.1	- 0.0035	+ 28.25	0.2656
+ 23.4	0.0000 reference	+ 28.25	0.2150
+ 39.1	+ 0.0085	+ 28.25	0.1520

The power recorded in Table I is the power only used by the heater control circuit from the +28 volt satellite bus. The data are presented in this manner to emphasize the quality of the insulation structure created in the MTP USO development. The remaining power required to operate the RF circuitry and power conditioning system of the MTP USO adds less than 0.4 watts from the + 28 volt supply.

The data charted in Figure 7 were accumulated using the Allan deviation method for estimating 'sigma,' the fractional frequency deviation of the USO, with time intervals of 'tau' seconds at a constant temperature environment of +25^{o}C. This data represent the time variation of the MTP USO's frequency stability. The two dominant characteristics of the time variation of a frequency source is its 'flicker floor' related to the quality of the resonator and its aging drift. In the data of Figure 7, the flicker floor of the USO is shown from 4 seconds to 40 seconds of tau, while the aging drift extends outward from about 200 seconds of tau. In an ideal USO with no temperature dependence, these two characteristics would appear as the intersection of two line segments, as shown. In the data of Figure 7, the temperature-dependent time variance can consequently be seen in the region of 40 to 200 seconds of tau within a magnitude of parts in 10^{13}. This time-variant temperature dependence correlates to the frequency change observed in Table I.

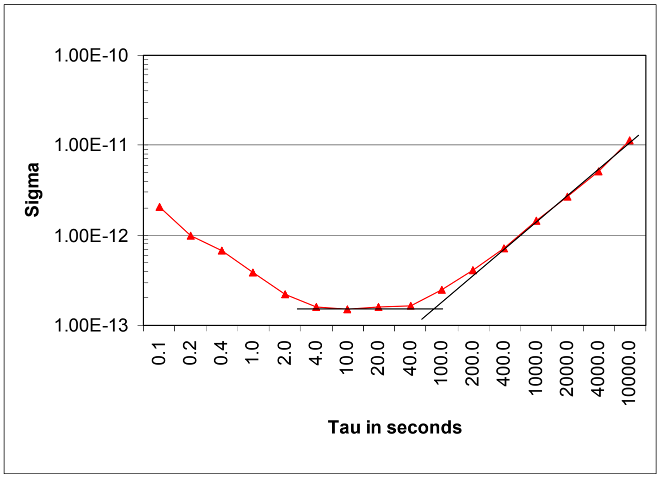

Figure 7. Allan deviation characteristic of the synthesized MTP USO.

III. CURRENT TECHNOLOGY DEVELOPMENTS

A USO WITH DIRECT DIGITAL SYNTHESIS FOR FREQUENCY AGILITY

Traditionally, JHU/APL USOs have relied on harmonic multipliers to generate their output frequency. Consequently, the specification of the quartz crystal resonator is directly related to communications channel selection. This leads to a time consuming process of mission design, frequency channel selection, and resonator purchase which must be executed early in the program with no flexibility for change during the hardware integration phase or after launch. JHU/APL's development of a USO that incorporates direct digital synthesis (DDS) for the NASA Mars Technology Program (MTP) task # 1243213 relieves this constraint. As resonators must go through a lengthy (and costly) screening process to select the best performing devices, it is impractical to screen and stockpile parts for every communication channel frequency. With a programmable frequency synthesizer, the resonator frequency can be standardized at a frequency of 5.000 MHz. As this is a relatively common frequency for scientific grade quartz resonators, these components are readily available in specialized, high-performance configurations. Furthermore, it becomes practical to maintain an inventory of these resonators and perhaps even a small inventory of the synthesized USO assemblies.

An even greater benefit of the synthesized USO output is the capability for in-flight programmability. The confluence of science missions scheduled for Mars will necessitate closer proximity among communication links, making flexible channel selection very desirable. For example, there may be instances where a single uplink frequency to multiple spacecraft is desired for command uploads, and certainly there will be times that different downlink frequencies are desired for data return from multiple spacecraft to multiple ground stations or rovers with potentially overlapping fields of view. With the frequency agility provided by a USO-driven DDS, this scenario could be accommodated through remote operation.

Table II provides a performance summary comparing several flight heritage USOs and the current performance of our effort to develop a USO that incorporates DDS technology. Each USO listed in this table represents important milestones within the evolution of USO development at JHU/APL over the last 15 years **[10]**. In the case of TOPEX, a phase-locked loop frequency synthesizer was developed to track the excellent fractional frequency characteristics of the USO while generating two non-harmonically

related output signals. The synthesizers of TOPEX were fixed, such that they could not provide any frequency agility while in orbit **[11]**. For the USOs involved with the Gravity Recovery and Climate Experiment (GRACE), a more compact oven structure was used with a conventional harmonic multiplier scheme. Currently, a slightly lighter version of this USO is being fabricated for use in the New Horizons mission to the Pluto-Charon system and is scheduled to launch in January of 2006. A resolute attempt at conserving weight and power was realized in the Planet B USO for use in the Japanese Nozomi satellite, with the condition that the USO could only operate in vacuum and with secondary power provided.

TABLE II. Performance comparison of USOs over 15 years of development.

Program	Frequency Synthesis	Mass (kg)	DC power (W)	Phase noise@10Hz* (dBc/Hz)
TOPEX**	Y	3.0	5.4	-116
GRACE	N	2.2	2.3	-112
New Horizons	N	1.5	2.7	-115
Planet B	N	0.46	0.5	-118
USO with DDS**	Y	0.59	0.85	-118

*Scaled for 76 MHz carrier
**Mass and power are sum of USO and synthesizer assemblies

In comparison to these predecessors, the USO with DDS represents an uncompromised frequency reference providing the flexibility of programmable frequency synthesis while in mission, compact mass efficient design, and lowered power consumption without the loss of ambient air operation. In addition, our investigation into DDS architectures has shown that it is possible to pass the desirable signal integrity of a very low noise reference onto an array of closely spaced communication channels. The spurious content commonly observed in a DDS can be controlled from unduly contaminating these desired channels by the proper selection of the control word passed into its accumulator. Further, the determination of this control word is calculable in advance of channel assignment through a method based in discrete Fourier transform derived in **[12]**.

A typical single side band phase noise measurement of our DDS implementation is shown in Figure 8. The largest spur, at approximately 1.5 MHz, is an up-conversion product from the method by which we introduce the DDS signal into the synthesizer output. The integrated double side band phase error from 1 Hz to 2 MHz, excluding this up-conversion product, varies from 0.015° rms to 0.022° rms over the desired range of 35 consecutive channels, spaced uniformly about 76.50 MHz.

We extend these integrated noise results to a possible application of the USO with DDS in a Ka-band transmitter using direct carrier multiplication. A 0.023° rms phase error in the USO output signal translates to only 0.1 dB degradation in the received bit energy over noise for a Ka-band phase-modulated signal in a 2 MHz single-sided data bandwidth. This indicates that our DDS is acceptable for deep space communication telemetry and low phase noise applications **[13]**.

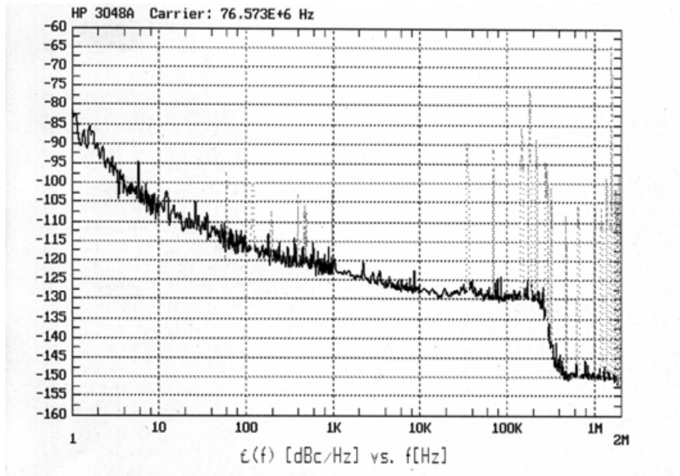

Figure 8. Typical channel phase noise from mix/multiply/DDS architecture.

A Disciplined USO for the Reduction of Long-term Drift

The objective of this research effort is to design and produce a USO with the enhanced performance of a Kalman-filter-based frequency control system. It is the goal of this work to provide a proof of concept for a highly reliable, space-based frequency reference that could be used as an alternative to rubidium gas cell atomic clocks.

Figure 9 illustrates the goal to provide the extended reliability of the JHU/APL quartz-based USO with the accuracy and long-term stability of an atomic clock. Specifically, we believe the success of our project could be used in projects similar to MILSTAR and GPS Block IIR satellites. Additionally, the ability to adjust the numerical operation of the frequency control system will allow a clock driven by our disciplined USO to be adapted to emergent, nonstationary stochastic time and frequency drift processes encountered during mission life.

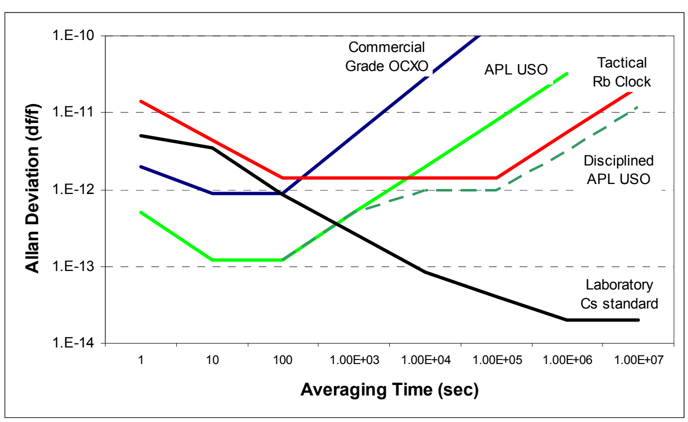

Figure 9. Comparison of proposed disciplined USO to other frequency sources.

The operational utility of the disciplined USO is centered on the expected life and reliability of quartz frequency sources as compared to atomic frequency standards, specifically rubidium gas cells. In the NAVSTAR GPS spacecraft, four atomic clocks are resident on each satellite, of which only one is kept in operation. The principal reason for this is that there is a limited life associated with the physics packages of these atomic clocks, measured in periods of less than 10 years **[14]**. In contrast, the USOs of JHU/APL have demonstrated continuous, high-quality operation with life exceeding decades, as stated earlier in the TRANSIT program, whose satellites remained in monitored operation from the 1960's through the mid 1990's **[1]**.

The published work of the frequency control community provides support for Kalman filtering over other minimum squared error methods as a desired approach for the prediction of a clock's behavior and control, citing its ability for a robust optimized estimate under adverse measurement conditions with irregular intervals **[15]**. Other work has shown that the process of logarithmic aging drift can be uniquely addressed within the Kalman filter algorithm with good results **[16]**. Our interest in the Kalman filter approach to improving the performance of the USO rests on this work with the inclusion for other frequency behaviors such as temperature stability, radiation sensitivity, and launch dynamics. Figure 3 shows a fourth-degree polynomial fit to the Mars Global Surveyor USO frequency over a period of 8 years. The frequency performance is clearly a smooth and continuous behavior with time, ideal for Kalman filter estimation.

Operationally, the estimators of the adaptive control system would be initialized during ground characterization and could be updated in flight, based on observed differences from an ensemble of ground-based clocks. Our research effort simulates control with USO oscillator data and examines the frequency drift performance obtained while varying the time interval between estimator updates. Additionally, we plan to build prototype hardware that includes integrated circuitry suitable for executing the adaptive control system and demonstrates the advantages of a disciplined USO.

The most evident measure of success in the development of a disciplined USO will be in achieving the improvement in the long-term frequency drift indicated in Figure 9. This will in effect create a new breed of space-based clocks based on the reliability of piezoelectric resonators. In this manner, just as the original USO enabled the ability of space-based time and navigation, the disciplined USO could promote new applications in the areas of deep space communication and remote planetary navigation.

FUTURE RESEARCH ACTIVITIES FOR DEEP SPACE MISSION NEEDS

New Packaging for Science Grade Precision Resonators

Advancement in the enclosure for housing the precision quartz resonator used in the JHU/APL USO is needed. The current USO quartz resonator utilizes a glass "pinch-tube" enclosure with multiple glass-to-metal header stages to achieve the excellent frequency stability we have reported throughout this paper. Nonetheless, the construction of this enclosure is inefficient in its use of volume, susceptible to fracture and requires cumbersome shock mounts to survive launch dynamics. The use of metal leads that breach the housing to provide electrical connection compromises the essential hermetic quality of the glass housing. Finally, the availability of the materials used to construct this package are becoming scarce as the technology, based on the production of electron tubes, is all but extinct in industrial practice.

The current industrial standard using nickel-clad, oxygen-free copper housings known as "cold-weld enclosures" has been tried several times within the JHU/APL USO, always with substandard results. The reason attributed to these unsuccessful trials has been the inability to process these metal enclosures at temperatures exceeding +230°C. This temperature limit is due to the copper alloy softening and, thus, mechanically collapsing under atmospheric pressure after evacuation. Consequently, contaminants which

are detrimental to the resonator's stability performance cannot be purged using high temperature processing, like that of the current glass enclosure.

The development of a surface-mountable enclosure that eliminates the electrical connection lead seals, provides for significant reduction in volume, and enhances the use of the high temperature processing to achieve the frequency stability performance of the current ultra-stable quartz resonator is the most desirable approach to resolving the USO's requirement for a rugged resonator package.

Alternative Piezoelectric Materials

Quartz suffers from a number of intrinsic limitations. Quartz can coexist in multiple, distinct phases at room temperature, including trigonal and hexagonal symmetry. These phases are piezoelectric, but have vastly different material properties and, therefore, result in distinctive attributes in temperature stability and electrical behavior. A further complication arises because the trigonal form can occur in both right-hand and left-hand forms in the same crystal material. The existence of these two forms within the same crystal creates a phenomenon known as 'twinning' that seriously degrades the resonator quality factor and resonator stability with respect to environmental characteristics. 'Twinning' provides an entrapment for contaminants and creates the need for stress-free handling of resonator blanks during processing, limiting the use of certain advantageous machining methods such as ultrasonic milling and laser trimming. Contaminants entrapped within the quartz crystal increases the sensitivity of the resonators to irradiation and other stimuli. Since quartz irreversibly transitions to a non-piezoelectric phase at 573ºC, high-temperature processing methods that can be used to effectively eliminate detrimental chemical reactions in the resonators must be avoided.

An investigation into piezoelectric materials promises superior resonator performance to quartz in precise timekeeping and frequency control for spaceborne applications. Certain manmade oxides (langasite, langanite, langatate, and III-V compounds such as gallium orthophosphate) exhibit superior electromechanical coupling in a single material phase around room temperature. Their elevated thermodynamic phase transition temperature, compared to quartz, enables higher temperature processing to reduce the effect of electro-chemical reactions and purge contaminates from resonators built from these materials. The elevated transition temperatures and favorable piezoelectric properties have already demonstrated resonators with higher quality factors and better frequency stability than quartz. Furthermore, these materials are expected to exhibit better radiation immunity.

All of the alternate materials proposed for investigation exist in a single phase right up to their melting points, which range between 790º and 1450ºC. This allows for the use of higher temperature processing of resonators produced from these materials that results in surfaces that are extremely clean from residual chemical contaminants. Moreover, the electro-mechanical coupling is three to six times better than that of quartz. Consequently, resonators realized with these materials are expected to yield commensurately higher figures of merit than quartz. Indeed, langatate, despite the infancy of its development, has already demonstrated a quality factor that is two times higher than the ultimate limit predicted (but not attained) for quartz, as discussed in **[17]**.

IV. SUMMARY

JHU/APL is actively engaged in the support of piezoelectric-based USO technology for civilian and military space applications. We believe that JHU/APL ultra-stable oscillators using scientific grade quartz resonators offer the most reliable method for frequency control for deep space projects. The

documented reliability and versatility of our USO is currently being enhanced through the following technology developments:

1.) The integration of a direct digital synthesizer to allow for flexibility in the assignment of channel selection both before flight and during operation in space;

2.) The introduction of an adaptive, discipline architecture to reduce the long-term drift behavior of the USO to under 1×10^{-11} for time intervals extending to 30 days.

In addition, the JHU/APL USO would substantially benefit from research in advanced resonator packaging to reduce size and an investigation into alternative piezoelectric materials that could lead to resonators that exceed the performance levels presently achieved with quartz.

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The measurement of long-term oscillator frequency performance requires an extended effort, as it must be calculated from the performance of the sub-systems fed by the USO and/or manipulated to remove the effects of orbital dynamics. The authors wish to acknowledge Lisa Cox of Lockheed-Martin; Joe Twicken of Stanford University; and Sami Asmar, Bill Hullinger, and Gerhard Kruizinga of NASA-JPL. Our development of the USO with direct digital synthesis, described in this paper, was supported by the NASA's Mars Technology Program, Advanced Technology Development Project under contract number 1243213.

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